Journal of the Torrey Botanical Society 135(3), 2008, pp. 401–410

Fire history from soil charcoal in a mixed hardwood forest on the Cumberland Plateau, Tennessee, USA[1]

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HART, J. L. (Department of Geography, University of North Alabama, Florence, AL 35632), S. P. HORN, AND H. D. GRISSINO-MAYER (Department of Geography, University of Tennessee, Knoxville, TN 37996). Fire history from soil charcoal in a mixed hardwood forest on the Cumberland Plateau, Tennessee, USA. J. Torrey Bot. Soc. 135: 401–410. 2008.—In this study, we documented the presence of macroscopic (> 2 mm) charcoal, quantified charcoal mass, and radiocarbon-dated charcoal macrofossils in 10 soil cores to develop a coarse-resolution fire history for a mixed hardwood forest on the Cumberland Plateau in Tennessee. Macroscopic charcoal occurred in all 10 soil cores. Total dry mass of macroscopic charcoal varied by core and by depth layer. Charcoal fragments were most abundant in two non-adjacent cores (separated by ca. 80 m), a finding that may be evidence of a patchy fire regime in the study area. AMS radiocarbon dating of the five deepest charcoal samples indicated that the earliest recorded fire in the study site occurred around 6735 cal yr BP (calibrated years before 1950). Charcoal in surface soils was not dated but one deep sample indicated a fire during the historic period at approximately 174 cal yr BP. No overlap occurred within the 2-sigma calibrated age ranges of the dated charcoal samples, indicating a minimum of five separate fire events have occurred on the site during the last 6700 plus years. This was the first study to use soil charcoal to document past fire events in hardwood forests of the Cumberland Plateau and the first to examine the prehistoric fire regime of *Quercus* stands in the region at a local-scale. Our results provide a basis for reconstructing long-term fire histories at the stand-scale in *Quercus*-dominated forests of eastern North America.

Key words: Appalachians, charcoal, Cumberland Plateau, disturbance, fire history, *Quercus*, Tennessee.

Recently, the role of fire in hardwood forests throughout the eastern U.S. has received increased attention because of successional changes believed to be associated with fire suppression that began in the early 1900s (Lorimer 1985, McCarthy et al. 1987, Crow 1988, Abrams and Downs 1990, Cho and Boerner 1991, Lorimer 1993, Goebel and Hix 1997, McEwan et al. 2007a). Fire as an ecosystem process in mixed hardwood stands of eastern North America is not well understood. Although *Quercus* species dominate forest overstories throughout the Central Hardwood Region, a lack of *Quercus* advanced regeneration has been reported (e.g., Lorimer 1984, Abrams and Downs 1990, McCarthy and Bailey 1996, Abrams 2003, Pierce et al. 2006). Fire suppression has allowed more shade-tolerant species, such as *Acer saccharum* Marsh., *Acer rubrum* L., and *Fagus grandifolia* Ehrh., among others, to establish and become abundant in the understory of *Quercus*-dominated forests. Fire suppression is also thought to have allowed forest canopy gaps to be filled by *Liriodendron tulipifera* L. and other early successional, gap-phase species rather than by *Quercus* (Loftis 1990, Loftis 2004). The prevailing hypothesis is that *Quercus* stands were historically maintained by frequent, low-intensity fires that removed more mesic and fire-intolerant species from the understory and effectively reduced competition for the more fire-tolerant *Quercus* species (Crow 1988, Abrams 1992, Brose et al. 2001, Lorimer 2001). An understory densely populated with shade-tolerant species inhibits the establishment of *Quercus* individuals (Lorimer 1993, Lorimer et al. 1994). Although *Quercus* individuals are often abundant in seedling layers of closed canopy forests, they are generally unable to recruit to larger size classes and may be considered ephemeral in the absence of fire or other

[1] This research was funded by the NSF under grant BCS-0602445; J. Hart was supported by NSF grant DGE-0538420. Radiocarbon dates were provided by the NSF-Arizona AMS Laboratory.

[2] We thank Wayne Clatterbuck, Carol Harden, Sara Hart, two anonymous reviewers, and the associate editor for suggestions that improved the manuscript.

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Received for publication January 29, 2008, and in revised form April 25, 2008.

large-scale disturbances (Cho and Boerner 1991, Goebel and Hix 1997, Hutchinson et al. 2003). These observations have led many forest managers to implement prescribed fire in an attempt to maintain and restore *Quercus* (Brose and Van Lear 1998, Hutchinson et al. 2005, Albrecht and McCarthy 2006).

Undoubtedly, fire by natural or anthropogenic ignitions has occurred in mixed hardwood stands of the southern Appalachian Highlands (Delcourt and Delcourt 1997, Delcourt and Delcourt 1998, Delcourt et al. 1998, Lafon and Grissino-Mayer 2007), but characteristics of the fire regime (such as frequency, magnitude, and spatial extent) are poorly understood. This information is needed to manage forests according to historic disturbance regimes, for the regeneration and maintenance of *Quercus* species, and for the proper classification of forests based on assumed species composition at stand maturity. The mixed-hardwood slope forests of the Cumberland Plateau do not include *Pinus* species or other taxa that scar easily during fires. Fire scars of *Quercus* species have been used to reconstruct past fire events, but thick bark may prevent individuals from scarring during low-intensity fires (McEwan et al. 2007b). Also, the vast majority of forests throughout the region are young ($<$ 100 years), with even the oldest trees in stands postdating the last fire. Fire histories have been constructed in the region based on microscopic charcoal in lake sediments (e.g., Delcourt and Delcourt 1997, Delcourt and Delcourt 1998, Delcourt et al. 1998). However, lakes receive microscopic charcoal inputs from large source areas and thus the records of fire history in microscopic charcoal profiles are not spatially explicit (Clark 1988, Clark and Royall 1996). In addition, fires in *Quercus* litter are rarely intense and microscopic charcoal production from fire events may be quite low (Abrams and Seischab 1997). Thus, lakes may not record all low intensity *Quercus* litter fires.

In this study, we used macroscopic charcoal recovered from soil cores as an indicator of past fire events. We focused on macroscopic charcoal sufficiently large to be retained on a 2 mm mesh screen because charcoal of this size is not readily transported by wind during or after fires or by overland flow on hillslopes. Such charcoal is generally considered primary charcoal (i.e., introduced during or shortly after a fire event), and its presence in soils is evidence of fire at the stand-scale (Patterson et al. 1987, Clark 1988, Sanford and Horn 2000, Gavin 2003, Gavin et al. 2003, Talon et al. 2005). Charcoal particles $>$ 0.5 mm are rarely transported by wind more than 30 m during fire events (Ohlson and Tryterud 2001). Larger charcoal fragments are likely formed in situ and indicate fire at the sampled location (Gavin et al. 2003). In addition to high spatial resolution, macroscopic charcoal also provides long-term fire records. Mean residence time of macroscopic charcoal varies by location, but charcoal may be preserved in mineral soils for 3,000–12,000 years (Gavin et al. 2003, DeLuca and Aplet 2008).

One previous study (Welch 1999) documented the presence or absence of macroscopic charcoal in *Pinus*-dominated stands on the Cumberland Plateau. However, the present study is the first to document and date macroscopic charcoal in soil of a mixed hardwood forest on the Cumberland Plateau and the first to examine the prehistoric fire regime at a local-scale using soil charcoal in *Quercus* stands of eastern North America. The overall goal of this study was to test the potential of macroscopic soil charcoal as a technique to reconstruct fire history in *Quercus*-dominated forests. The specific objectives of the study were to: 1) document the presence of charcoal in soil samples as evidence of fire occurrence, 2) compare charcoal mass at different depths and at different locations to infer temporal and spatial patterns of past fire events, and 3) obtain accelerator mass spectrometry (AMS) dates on the deepest charcoal samples to reconstruct a coarse-resolution fire history in a transitional hardwood forest on the Cumberland Plateau.

Materials and Methods. Study Site. The study was conducted in the Pogue Creek Natural Area (PCNA) located in Fentress County, Tennessee in the north-central portion of the state (Fig. 1). The PCNA is a 1,505 ha nature reserve designated as a State Natural Area and managed by the State of Tennessee, Department of Environment and Conservation, Division of Natural Areas. The PCNA is a component to a large contiguous network of public lands that also includes the Big South Fork National River and Recreation Area, Pickett State Park, Pickett State Forest, and Daniel Boone National Forest.

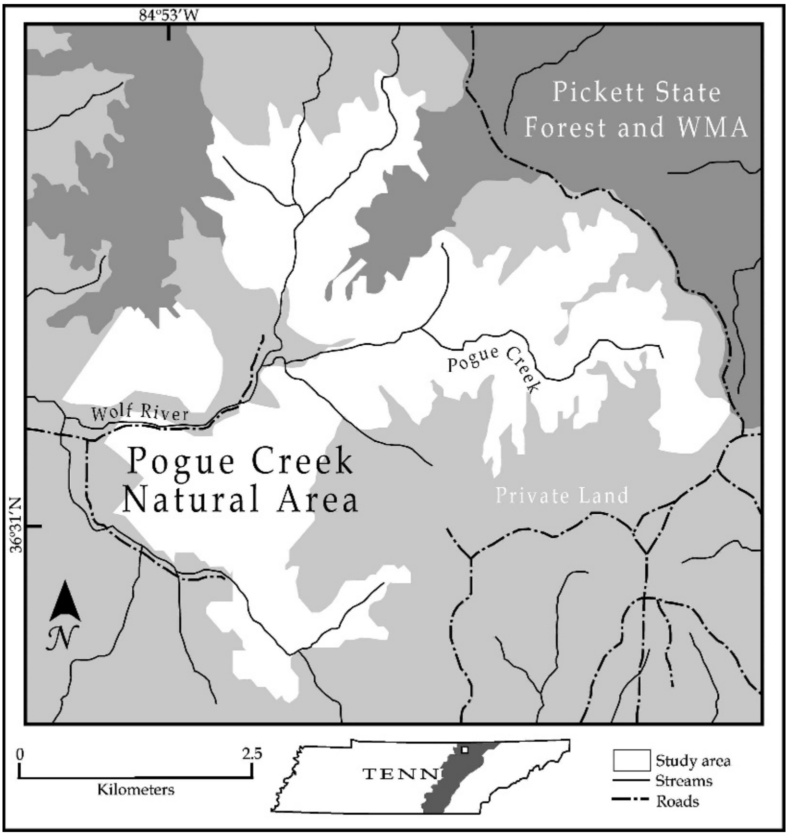

FIG. 1. Map of the Pogue Creek Natural Area in Fentress County, Tennessee. Shaded area on Tennessee inset map is the Cumberland Plateau physiographic section.

The PCNA is located within the Cumberland Plateau section of the Appalachian Plateaus physiographic province (Fenneman 1938). The underlying geology consists largely of Pennsylvanian sandstone, conglomerate, siltstone, shale, and coal of the Crab Orchard and Crooked Forked Groups (Swingle et al. 1966). The area has irregular topography and is characterized by long ridges and valleys of varied widths (Fenneman 1938, Smalley 1986). Streams are deeply incised and ridges are capped with erosion resistant sandstone. The reserve contains a number of unique geologic features including arches, caves, large boulders, and rock outcrops that are scattered along the slopes. In the region, soils are highly variable but generally are acidic, highly leached, and low in fertility (Francis and Loftus 1977, Smalley 1982). The cobbly loam soils of the PCNA, part of the Grimsley-Jefferson-Bouldin association, are acidic and relatively low in organic matter (USDA 1995, Hart 2007). Slope gradients in the study area range from 15–60%. Elevation of study plots ranged from 270–450 m amsl.

The climate is classified as humid mesothermal (Thornthwaite 1948), with moderately hot summers and short, mild to moderately cold winters and microclimate is strongly influenced by local topography. The average frost-free period is 160 days (from early-May to late-October) and the mean annual temperature is 13°C. The July average is 23°C and the January average is 2°C (USDA 1995). The area receives steady precipitation throughout the year and experiences no distinct dry season. Mean annual precipitation is 137 cm and mean annual snowfall is 50 cm (USDA 1995). Late spring and summer are characterized by heavy rains that are often accompanied by moderate to severe thunderstorms. On average, thunderstorms occur 55 days annually (Smalley 1982).

Braun (1950) classified the area as part of the Cliff Section of the Mixed Mesophytic Forest Region. However, true mesophytic species only dominate on protected sites. The slope forests of the region are dominated by mixed *Quercus* species with *Q. alba* L. being the most abundant followed by *Q. coccinea* Muenchh. and *Q. velutina* Lam. (Hinkle 1978, Hinkle 1989). Many forest stands on this section of the Cumberland Plateau are dominated by mixed *Quercus* and *Carya* species and at the landscape-level vegetation is intermediate between mixed mesophytic and *Quercus-Carya* forest types. Species composition is largely controlled by topographic characteristics and factors related to soil water availability (Hinkle 1978).

Species composition, stand structure, and disturbance history of the PCNA were quantified by Hart and Grissino-Mayer (2008). The forest was dominated by *Carya ovata* (P. Mill) K. Koch, *Q. rubra* L., *Q. alba*, and *Q. montana* Willd. The sparse sapling layer was dominated by *Acer saccharum*. In the seedling layer, *A. saccharum* and *A. rubrum* represented almost 69% of all individuals. The forest established in the 1920s and the disturbance regime during development was characterized by gap-scale disturbances that influenced only neighboring trees (Hart and Grissino-Mayer 2008). No signs of fire during stand development were detected from field observations (e.g., fire scarred trees or logs) or from the investigation of 17 tree cross sections collected and analyzed during a previous study (Hart 2007).

Field and Laboratory Methods. Soil charcoal was quantified from 10 soil cores collected from the PCNA. All cores were collected from mid-slope positions at points located along transects spread randomly throughout a mixed hardwood stand and the location of each point was recorded. Transects were oriented parallel to slope contour and were established in a previous study (Hart 2007). We subjectively sampled mid-slope positions because the mid-slope forests of the reserve are similar in composition to stands of the escarpment and dissected regions of the Cumberland Plateau. We limited the extent of our sampling to a stand with known species composition, structure, and disturbance history and because spatial resolution is one benefit of macroscopic charcoal. The cores were collected using a tubiform root corer following methods described by Horn et al. (1994). The core diameter was 8 cm and the samples were collected in contiguous 10 cm depth intervals to unconsolidated bedrock or an impenetrable clay layer (which was less than 50 cm depth for all cores). Each 10 cm increment was considered a separate soil sample, which resulted in a total of 30 samples. Each sample was stored in a labeled bag and transported to the laboratory for analyses.

Following the methods outlined by Horn et al. (1994), each sample was soaked in approximately 1.5 l of water overnight to disaggregate soil particles. We then wet-sieved each sample through a 2 mm mesh brass screen. All charcoal particles retained on the screen from each of the 30 samples were identified with the aid of a stereozoom scope and placed in labeled glass vials. The vials were dried in an oven at 100°C for approximately 24 hours. We then measured the dry weight of charcoal in each sample to the nearest 0.0001 g.

The presence or absence of macroscopic charcoal for each sample was used to document past fire occurrence. Total charcoal mass was compared among depth intervals within each core to examine temporal patterns. Total charcoal mass was also compared among all cores at the same depth interval to examine spatial patterns. We also classified tree-ring structure as either diffuse porous or ring porous for larger charcoal fragments that contained a minimum of one complete growth ring. Ring-structure was classified to determine possible taxa that were present at the time of past fires and that were killed or injured by them.

Five samples were submitted to the NSF-Arizona AMS Laboratory for radiocarbon dating using AMS. The high cost of AMS analyses precluded dating beyond what was supported by the NSF-Arizona AMS Laboratory through their program of student assistance. All but one sample constituted multiple charcoal pieces collected within a depth interval of a core. The five samples submitted for dating were selected because they were from the lowermost soil samples that contained charcoal and were judged likely to provide the best estimate of the maximum age of collected charcoal. Two charcoal samples were submitted from core 1 because it was the deepest sample. The maximum age of the charcoal at the site provided an estimate of the timing of the earliest recorded fires, although charcoal ages could predate fire ages by a century or more (inbuilt age error), depending on the age of the wood at the time it was burned (Waterbolk 1983, Gavin 2001). The ages are also used to determine if the collected charcoal represents distinct fire events in the reserve. Radiocarbon years were converted to calendar years using the CALIB radiocarbon calibration program (Stuiver and Reimer 1993, vers. 5.0.1) and the dataset of Reimer et al. (2004). We used the weighted mean of the calibration probability distribution to assign a single calendar year to each sample (Telford et al. 2004).

Results. Soil depth was rather shallow. Average maximum sampling depth was 24.9 ± 11.1 (SD) cm and ranged from 14 to 47 cm. Macroscopic charcoal was present in all 10 soil cores (Fig. 2). Charcoal occurred in 19 of the 30 soil samples (63%). The deepest soil core was core 1, which extended to a depth of 47 cm before hitting bedrock. Core 1 did contain charcoal in the deepest layer (40–47 cm). Charcoal was present in all depth intervals of cores 2, 4, 5, and 9. Only two cores (cores 3 and 7) did not contain macroscopic charcoal in the 0–10 cm depth interval. Half of the cores contained charcoal the two uppermost depth intervals. Macroscopic charcoal in core 1 occurred in alternating layers. No depth layer contained macroscopic charcoal across all cores and no clear pattern of charcoal presence or absence was evident. All charcoal did occur in mineral soil.

The total amount of macroscopic charcoal recovered was 4.06 g. Core 2 contained the largest amount of charcoal (2.76 g) followed by core 4 (0.78 g) (Fig. 2). The least amount of charcoal recovered was from core 6 (0.002 g), but cores 3 and 7 also had relatively small amounts. When charcoal from all cores was totaled by depth layer, a pattern of charcoal accumulation was revealed. The amount of charcoal was greatest near the surface and the amount of charcoal decreased with increased depth (Fig. 3). This pattern occurred in individual cores 2, 4, and 10 and emerged across all cores driven by the relatively large amount of charcoal in the uppermost layers of cores 2 and 4. In cores 3, 5, 7, and 9, however, charcoal mass was greatest in the deepest layer sampled. The largest piece of charcoal occurred in the 10–15 cm depth sample of core 5.

The total mass of macroscopic charcoal was plotted by core to analyze charcoal distribution (Fig. 4). Core 2 contained the most charcoal, but relatively small amounts of charcoal were recovered from cores 1 (which was in a similar slope position) and 3, the two cores nearest. The same pattern was evident for cores nearest core 4.

Although many charcoal fragments could not be taxonomically classified with confidence, visual examination of larger fragments (n = 12) revealed the wood was from individuals with diffuse porous growth-ring structures. Common diffuse porous species that inhabit the study site include *Acer saccharum*, *A. rubrum*, *Fagus grandifolia*, and *Liriodendron tulipifera*. The ring structure of the charcoal macrofossils indicate one or more of these species occurred on the site in the past and were components of stands disturbed by fire.

Radiocarbon assays indicate the dated charcoal samples represent five distinct fires in the reserve (Table 1). The calibrated age ranges (± 2 σ) of the samples do not overlap; three adjacent date pairs were separated by 1200 or more years, and the fourth adjacent pair was separated by 385 years. The oldest radiocarbon date was 6735 cal yr BP. This charcoal was collected from the deepest sample. The most recent date was 174 cal yr BP. However, this sample was not nearest the surface. Three dated samples were collected from the 20–30 cm or 20 cm to bedrock layer and the range of dates on those samples was 3259 years. Notably, the most recent fire date was recorded on a single charcoal macrofossil with diffuse porous ring structure.

Discussion. Most macroscopic charcoal mass occurred in the upper 0–10 cm. This may indicate that fire has occurred fairly recently at the site and was not common historically, although, charcoal did occur in the deepest sample (40–47 cm). However, macroscopic charcoal in soil does not typically form distinct bands of accumulation that may be linked to one fire event (Gavin et al. 2003). The preservation of distinct charcoal layers is rare in forest soils because of overland flow, bioturbation, and physical processes such as tree blowdown (Carcaillet 2001, Gavin et al. 2003).

The pattern of charcoal distribution with depth was similar for cores 2 and 4, with both cores showing highest charcoal mass in the 0–10 cm depth increment, and declining values with depth. These two cores also contained the largest total charcoal mass, even though they

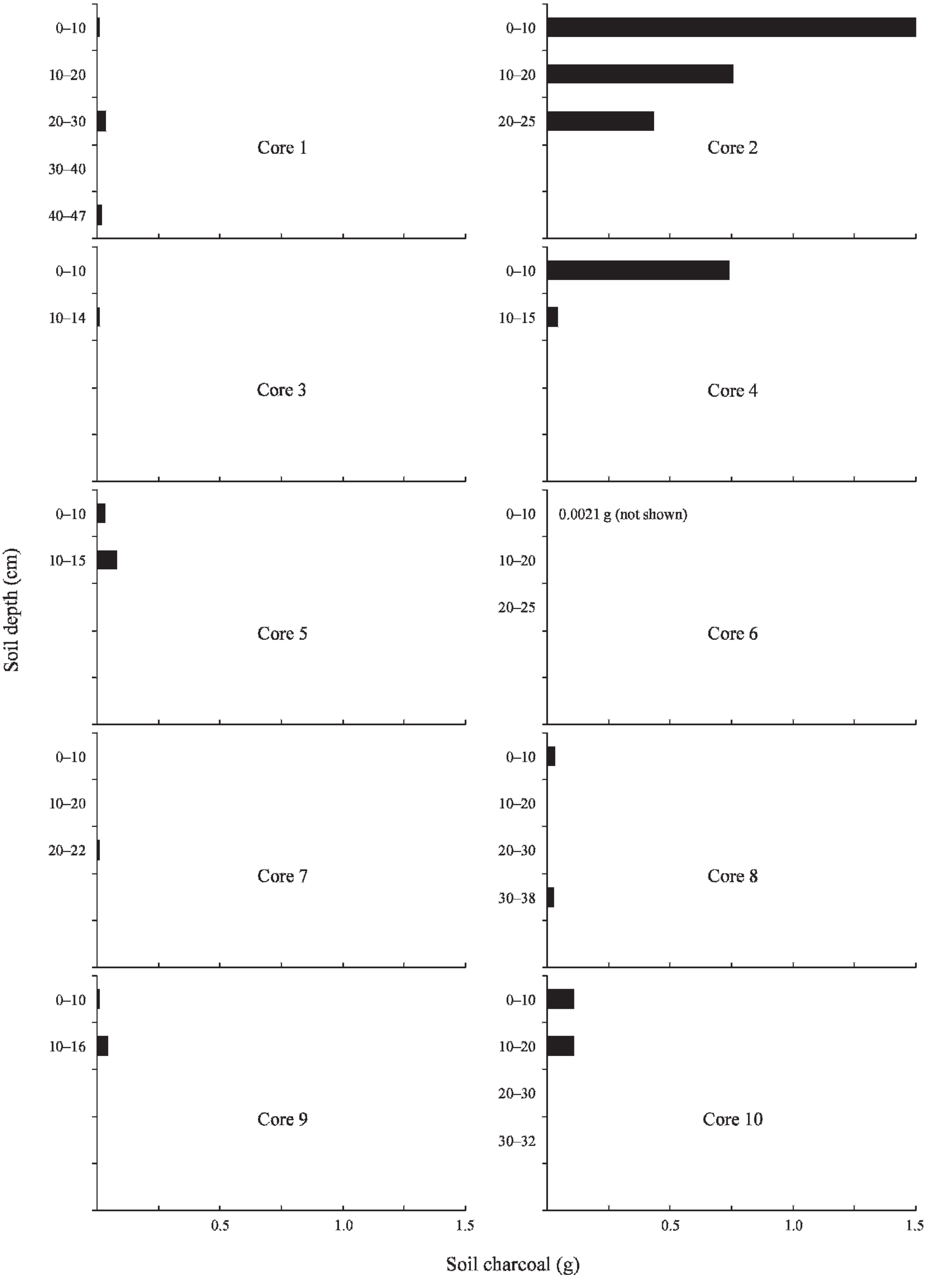

FIG. 2. Amount of macroscopic charcoal captured on a 2 mm sieve from 10 soil cores from a mixed hardwood forest on the Cumberland Plateau.

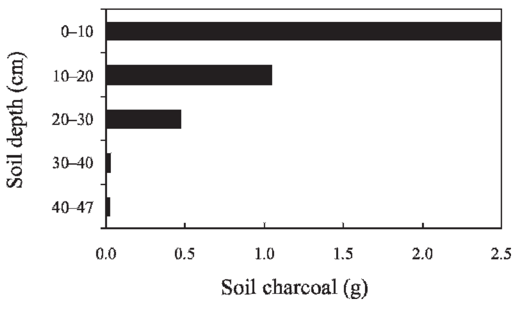

FIG. 3. Total macroscopic charcoal captured on a 2 mm sieve by depth from 10 soil cores from a mixed hardwood forest on the Cumberland Plateau.

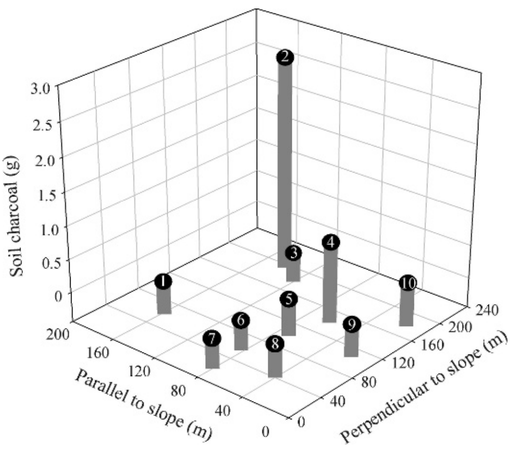

FIG. 4. Total macroscopic charcoal captured on a 2 mm sieve from 10 soil cores from a mixed hardwood forest on the Cumberland Plateau. Axes are distance (m) of the study area parallel and perpendicular to slope contour and total charcoal mass per core (g).

were not collected near one another. Core 3 was located between cores 2 and 4, but contained a relatively small amount of macroscopic charcoal. The spatial pattern of charcoal accumulation indicated that fires in the stand were small events that only influenced local areas. Welch (1999) recovered macroscopic charcoal from multiple topographic forms and slope positions on the Cumberland Plateau. In our study, all soil cores were collected from mid-slope positions, but microtopography may nevertheless influence charcoal accumulation.

The high amount of charcoal in the upper samples of cores 2 and 4 may be the result of the last logging episode at the site, which occurred in the 1920s. It is possible the slash was burned after logging or the site was burned for grazing purposes immediately following timber removal. Radiocarbon dating of near-surface charcoal would provide a test for this hypothesis.

The earliest fire dated by soil charcoal at the site was 6735 cal yr BP and the most recent fire dated was 174 cal yr BP. These dates reflect the time that carbon was fixed by the plant, not the time of the fire event. However, rot of heartwood is common for most tree species that inhabit the Cumberland Plateau, and the warm, humid climate causes rapid decomposition of snags and logs. Thus, we propose that the 'inbuilt age error' for these charcoal samples is minimal compared to the four to six centuries of inbuilt age possible in forests located in cooler environments or composed of species that decay more slowly (Gavin 2001). The inbuilt age of hardwood charcoal from mesic forests of the Cumberland Plateau may be no more than 100 years. The radiocarbon dates clearly indicate the occurrence of fires during the prehistoric and early European periods. No fire dates overlapped in their two-sigma age ranges, even after allowing for an additional error due to inbuilt ages (Gavin 2001), indicating that these were distinct events. Multiple pieces of charcoal were dated from four of our samples. However, based on the relatively long intervals between fire events we propose that charcoal fragments within the same sample were likely formed by the same fire.

Fires may have been set by Native peoples prior to European settlement (Delcourt and Delcourt 1997, Delcourt and Delcourt 1998) or by lightning, although lightning fires are believed to be relatively rare in the southern Appalachian Highlands (Van Lear and Waldrop 1989, Meier and Bratton 1995, Mitchener and Parker 2005). Fires during the early historic or prehistoric period could also be responsible for some of the undated charcoal in the 0–10 cm depth interval, owing to a slow rate of soil accretion on these mid-slope positions or to soil mixing from anthropogenic activities, treefall, and burrowing animals.

Additional AMS dates would provide a more detailed fire history for the site as further dating may yield unrecorded fire events. However, AMS dating can be cost prohibitive. The collection and dating of macroscopic soil charcoal is just one of several techniques that may be used to reconstruct fire history. Multi-

Table 1. Radiocarbon determinations and calibrations for Pogue Creek Natural Area charcoal samples.

Lab number[a]	Core and depth (cm)	$\delta^{13}C$ (‰)	Uncalibrated ^{14}C age (^{14}C yr BP)	Calibrated age range[b] $\pm$ 2 σ	Area under probability curve	Weighted mean calibration age[c]
AA-74050	P1: 20–30	−27.4	3216 ± 35	3485–3364 cal yr BP	0.953	3433 cal yr BP
				3554–3524 cal yr BP	0.047	
AA-74051	P1: 40–47	−26.3	5913 ± 40	6803–6653 cal yr BP	0.941	6735 cal yr BP
				6849–6813 cal yr BP	0.059	
AA-74053	P2: 20–25	−28.7	201 ± 31	25– −2 cal yr BP	0.169	174 cal yr BP
				221–140 cal yr BP	0.554	
				304–261 cal yr BP	0.277	
AA-74049	P7: 20–22	−25.2	1585 ± 33	1541–1401 cal yr BP	1.000	1468 cal yr BP
AA-74052	P8: 30–38	−24.6	2046 ± 33	2115–1926 cal yr BP	1.000	2009 cal yr BP

[a] Analyses were performed by the NSF-Arizona AMS Laboratory. All samples (except AA-74053) consisted of multiple pieces of charred wood.
[b] Calibrations were calculated using CALIB (Stuiver and Reimer 1993, vers. 5.0.1) and the dataset of Reimer et al. (2004).
[c] Weighted mean of the 2 σ calibration probability distribution.

proxy efforts that combine macroscopic soil charcoal with fire scarred trees and microscopic charcoal from lake sediments would be useful to create longer fire histories at different spatial and temporal resolutions. In addition to fire history reconstruction, macroscopic soil charcoal mass has the potential to be used to quantify soil carbon storage and its relationship to fire events (DeLuca and Aplet 2008).

Conclusions. The study showed that the site has burned in historic and prehistoric times and that macroscopic charcoal produced by those fires may be recovered from forest soils. Likely, fires at the site were patchy at a fine scale although additional testing is needed. The site is presently mesic and would not facilitate fire movement under normal (i.e., non-drought) conditions (Mitchener and Parker 2005). The identified charcoal was from species with diffuse porous ring structures. The forest is dominated by mixed *Quercus* and *Carya* species that do not exhibit this structure. The most abundant species currently at the site with a diffuse porous structure are *Acer saccharum*, *A. rubrum*, *Fagus grandifolia*, and *Liriodendron tulipifera*. Based on this observation, we suggest that one or more of these mesic species were present when past fires occurred at the site and one AMS date confirms at least one diffuse porous species was charred during the most recent fire event. We propose that fires burned stands composed of species not considered fire-tolerant.

AMS dates indicate the site has burned a minimum of five times in the last 6700 yrs. Together these data provide an initial, coarse-resolution fire history for a mixed hardwood forest on the Cumberland Plateau in Tennessee. Our work validates the use of this technique to document fire at the stand-scale in *Quercus*-dominated forests. This technique may be especially important to document local fire history at sites lacking other fire records. This work also provides a basis for assessing the utility of more detailed study of soil charcoal mass and taxonomy to reconstruct fire history and understand the influence of fire on *Quercus* forests of eastern North America.

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